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Title:	Convincing Search for Sterile Neutrinos at LANL Coherent Captain-Mills (CCM) Experiment
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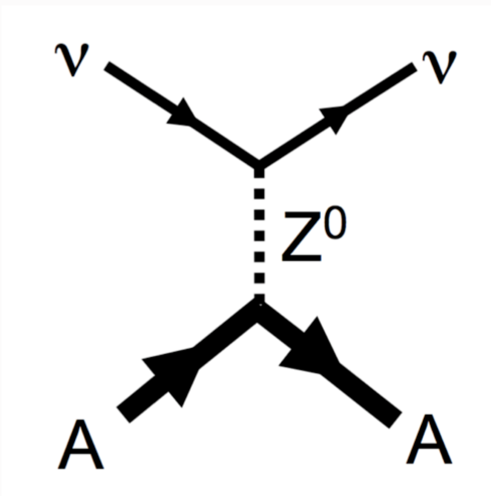
Convincing Search for Sterile Neutrinos at LANL
Coherent Captain-Mills (CCM) Experiment



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CAPTAIN = "Cryogenic Apparatus for Precision Tests of Argon Interactions with Neutrinos"

LANL Team

P-25, P-23, P-27, AOT

R.G. Van de Water (PI, Spokesperson), Elena Guardincerri (co-PI), Walter Sondheim, Tyler Thornton, En-Chuan Huang, T.J. Schaub, Mitzi Boswell, Bill Louis, Steve Elliot, Charles Kelsey, Charles Taylor**, Dan Poulson, Bob Macek**

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External Team

Mike Shaevitz (Columbia), H. Ray (U. Florida)Janet Conrad (MIT), **Robert Cooper, (LANL-NMSU, Co-Spokes),** Josh Spitz (U. Mich), R. Van Berg (U. Penn), M. Toups (FNAL), R.Tayloe (IU), and many students + PD's
Darryl Smith (Embry Riddle), Alexis Aguilar-Arevalo (UNAM – Mexico)

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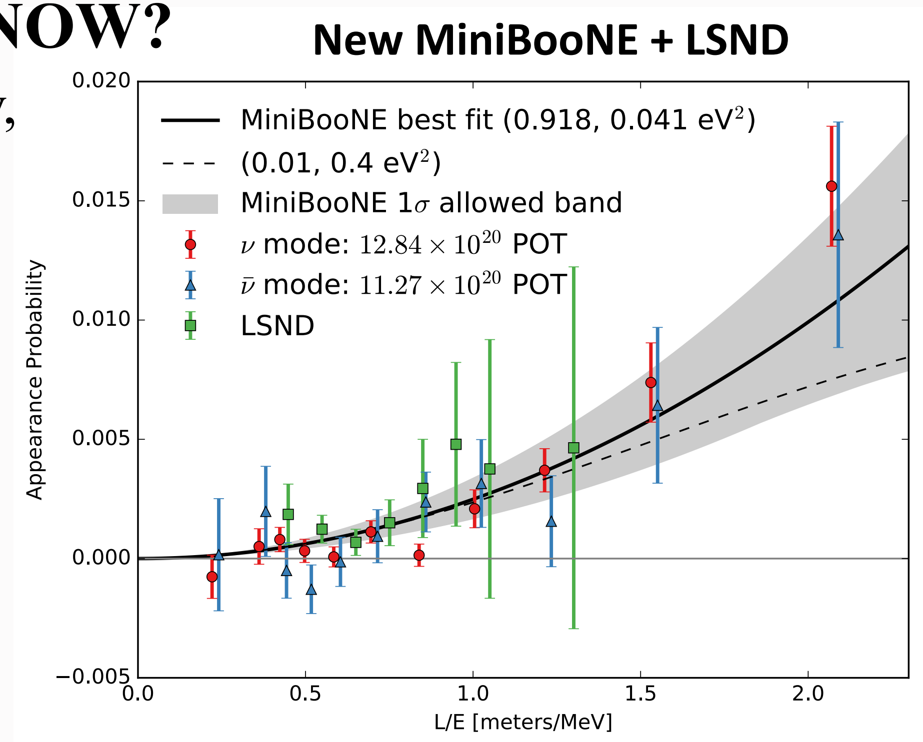
WHY NOW?

Short baseline anomalies did not go away, instead, 2018 MiniBooNE + LSND are consistent and combined ~6σ

An unambiguous experimental test is needed demonstrating:

$$\left\{\begin{array}{ccccc} \nu_\mu & \rightarrow & \nu_s & \rightarrow & \nu_e \\ \nu_e & \rightarrow & \nu_s & & \\ \color{red}{\nu_\mu} & \color{red}{\rightarrow} & \color{red}{\nu_s} & & \end{array}\right.$$



WHY LANL?

Coherent CAPTAIN-Mills is the only experiment being proposed that can test ν_μ disappearance with sufficient sensitivity at the LSND mass scale

CCM will be complementary to other neutrino programs around the world

CCM is unique, well-motivated, timely, and fully funded by LANL LDRD funding!

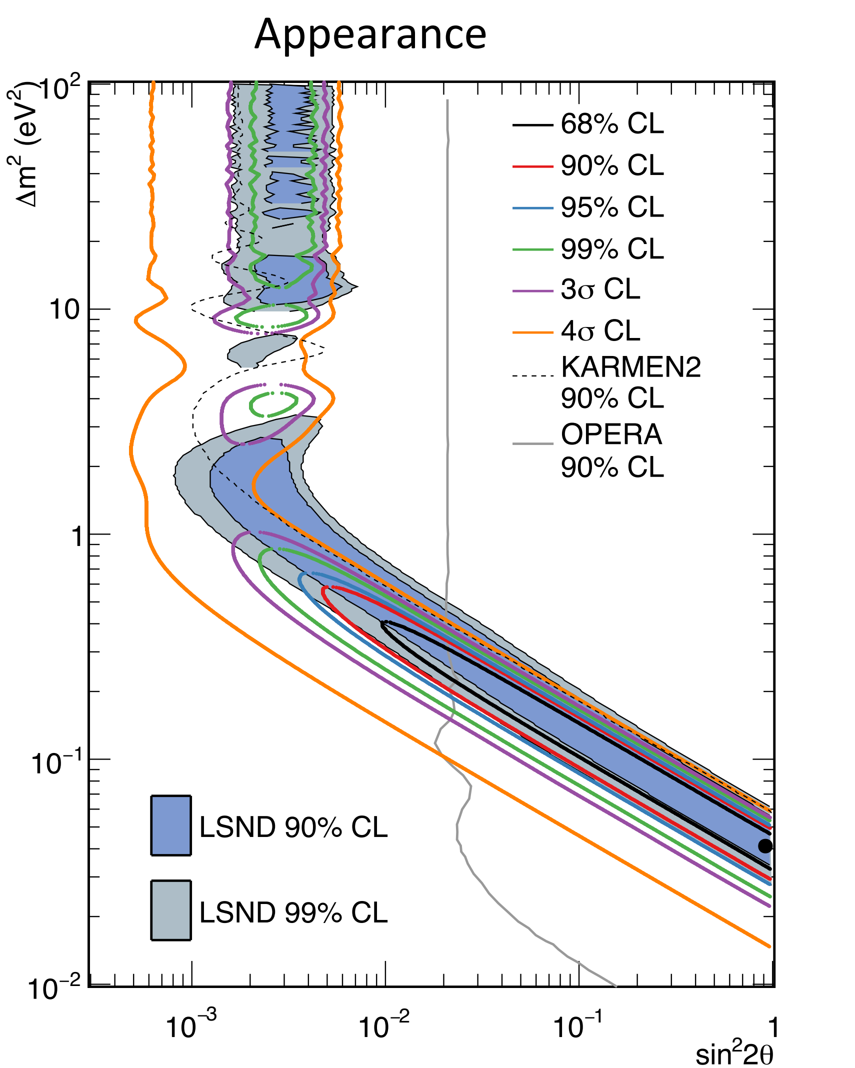
Testing the sterile neutrino hypothesis

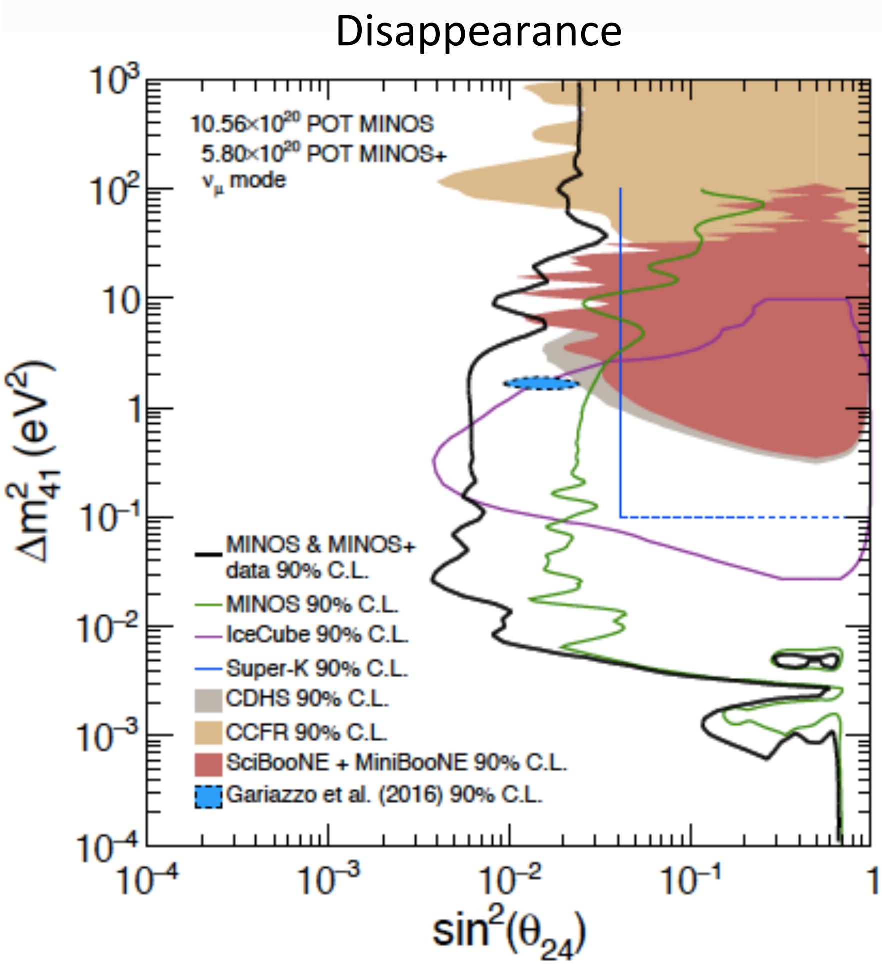
Past, current, and future experiments:

Oscillation Mode	Experiment Type	Past/Current Experiments	Signal Significance at LSND Mass Scale	Future Experiments (next 5 years)
$\nu_\mu \rightarrow \nu_e$	Short baseline accelerator	LSND, MiniBooNE, MicroBooNE	6.1 σ	SBN@FNAL program, JSNS[2]
$\nu_e \rightarrow \nu_s$	Reactor/source	Daya Bay, RENO, Double Chooz	~2-3 σ	PROSPECT, DANNS, SOLID, BEST, NEOS
$\nu_\mu \rightarrow \nu_s$	Short/Long baseline accelerator	SciBooNE+Mini-BooNE, MINOS+, IceCube	none	CCM

New experiment proposes 100 kg CsI detector at SNS (arXiv:1901.08094)

Severe Tension Between Appearance & ν_μ Disappearance Experiments in a 3+1 Model





arXiv:1710.06488v2

3+1 Models With ν_e Appearance Require Large ν_e & ν_μ Disappearance!

In general, $P(\nu_\mu \rightarrow \nu_e) \sim ¼\, P(\nu_\mu \rightarrow \nu_x)\, P(\nu_e \rightarrow \nu_x)$

Assuming that the 3 light neutrinos are mostly active and the N heavy neutrinos are mostly sterile.

More Exotic SBL Possibilities Than 3+N Models

(Sterile neutrinos may have other interactions!)

- Sterile Neutrino Decay
- Sterile Neutrinos NSI & New Gauge Bosons
- Altered Dispersion Relations (Resonant Oscillations)
- Pseudo-Dirac Neutrinos
- Light WIMP Production (Light WIMPs can behave like neutrinos)
- Lorentz Violation & CPT Violation
- Mass-Varying Neutrinos
- Neutrino De-Coherence
- etc.

Require $\nu_\mu \rightarrow \nu_s$ measurements at LSND energy to resolve different models

Coherent CAPTAIN-Mills experiment

Production mechanism:

charged pions decaying at rest $\Rightarrow$ monoenergetic neutrinos

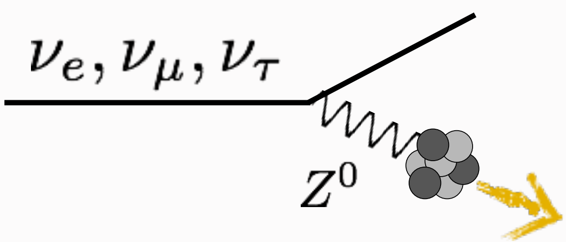
$$\mu^+ \longleftarrow \quad \pi^+ \quad \longrightarrow \nu_\mu$$

$$E_{\nu_\mu} = 30 \text{ MeV}$$

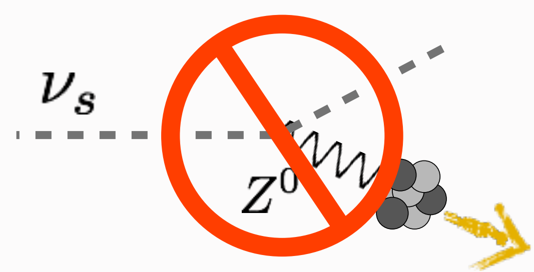
Detection mechanism:

Coherent Elastic Neutrino-Nucleus Scattering
"CEvNS"

present for all active neutrinos

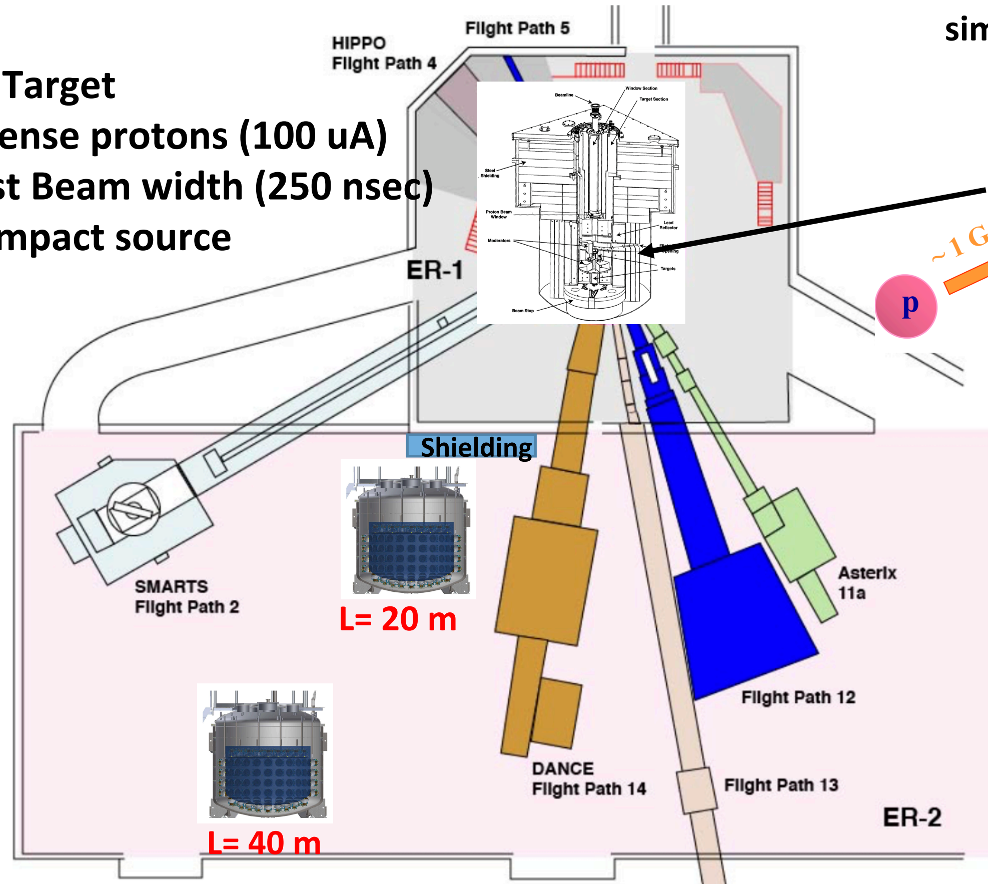


absent for sterile neutrinos

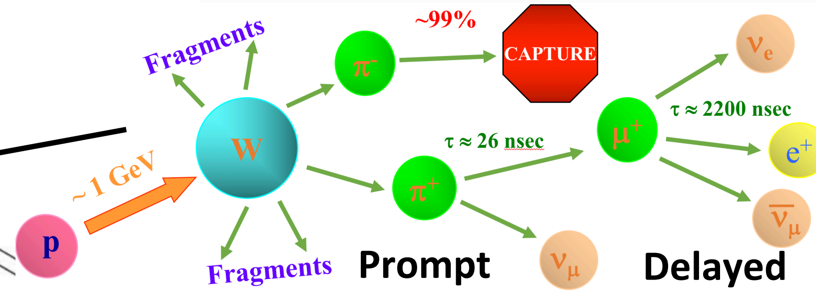


LANSCE-Lujan Facility a unique place to perform significant and timely test of Sterile Neutrinos

Lujan Target
- Intense protons (100 uA)
- Fast Beam width (250 nsec)
- Compact source

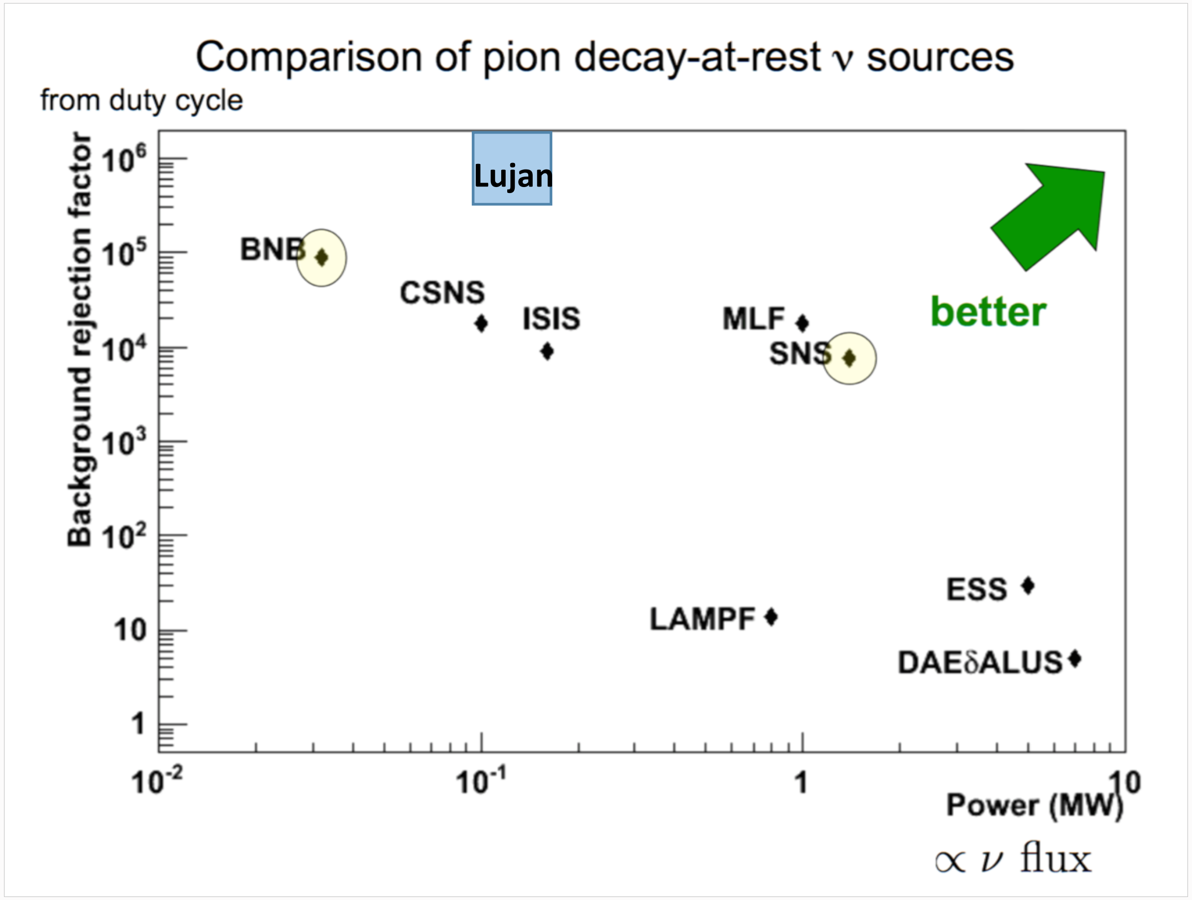


Intense source muon neutrinos: target MCNP simulation flux 4.74×10^{5} nu/cm^2/s at 20 m



Lujan Experimental Area
- Space for large 10-ton liquid Argon neutrino detector.
- Run detector in multiple locations.
- Room to deploy shielding, large overhead crane, power, etc

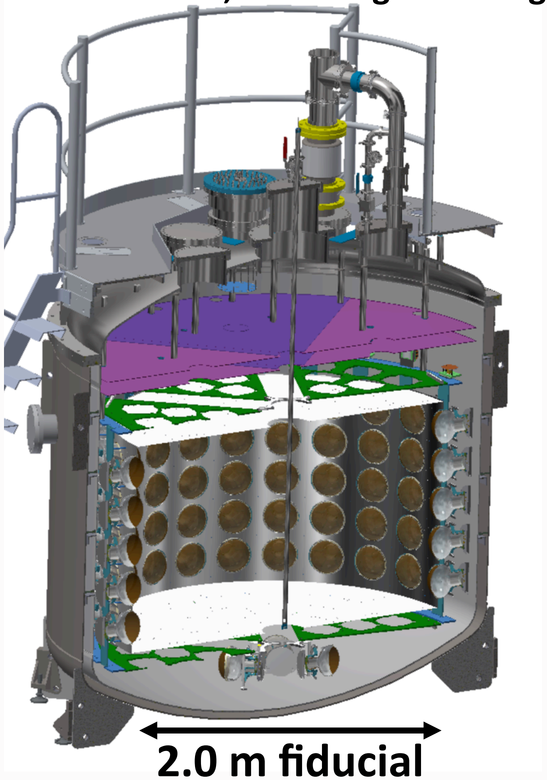
Lujan is a Competitive Neutrino Source
Low duty factor critical for background rejection



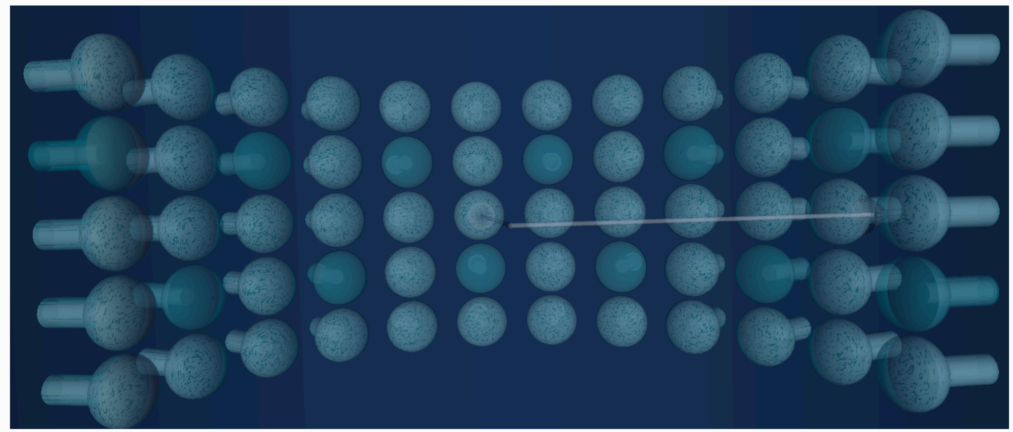
- Neutrino experiments require high instantaneous power (signal/background)
  SNS = 0.029 kJ/nsec; Lujan= 0.028 kJ/nsec
- Plan to run Lujan at ~100 nsec beam width with minimal intensity reduction

Detecting Coherent Neutrinos: Maximizing Scintillation Light Detection!

- **120 R5912 PMT's, wavelength shifting TPB foils**



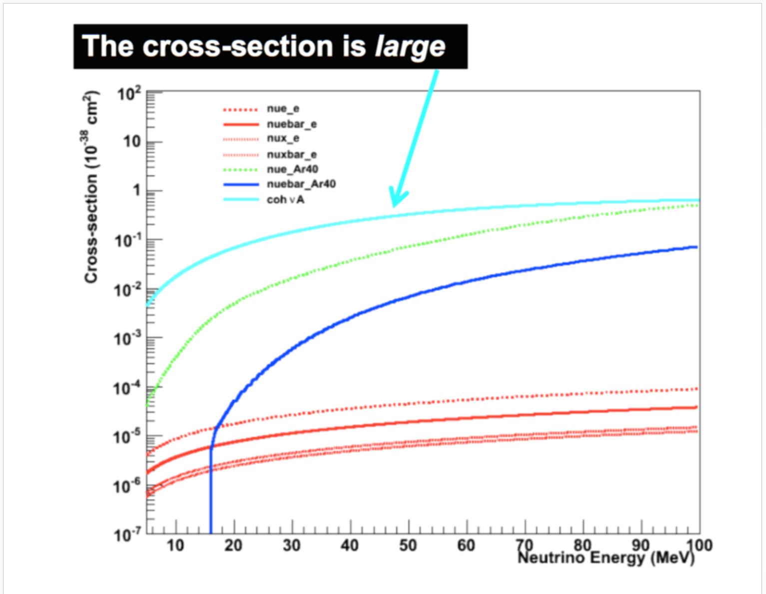
RAT/GEANT Detector Simulation



Simulations predict ~0.5 PE/keVnr

- **Liquid Argon scintillates at 128 nm with 40,000 photon/MeV, or 40 photons/keV.**
  - fast 6 nsec and slower ~1.6 usec time constants.
  - TPB wavelength shifting coating on PMT's and foils to convert to visible light.
- **Detailed RAT/GEANT4 simulation predicts 10-20 keV detection threshold.**

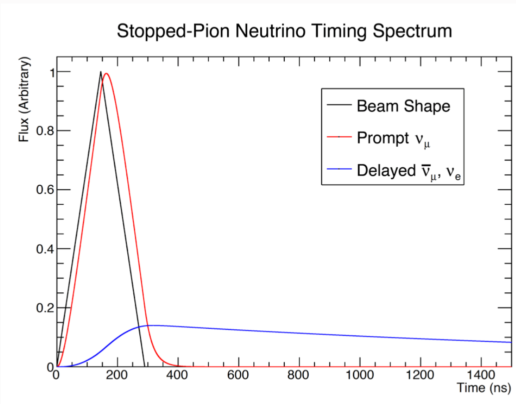
Expected CAPTAIN-Mills LAr Event Rates (80 kW @ 8 months, 7 tons LAr)

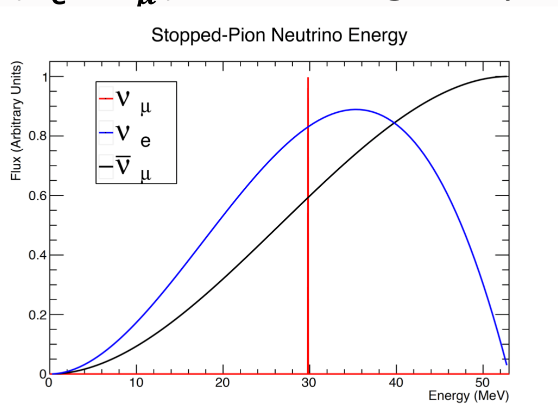


Large LAr **coherent eleastic neutrino-nucleus scattering (CEvNS)** cross sections -> 1000's events!

Reaction	L = 20 m (events/yr)	L = 40 m (events/yr)
Coherent ν_μ (E = 30 MeV)	2709	677
Coherent $\nu_e + \bar{\nu}_\mu$	9482	2370
Charged Current ν_e	257	64
Neutral Current ν_μ	36	18
Neutral Current $\bar{\nu}_\mu$	79	20

- Two oscillation analysis samples with different strategy/backgrounds:
  - **PROMPT** with beam (mono-energetic $\boldsymbol{\nu_\mu}$) – scattering end point energy 50 keV
  - **DELAYED** 4 usec after the beam ($\boldsymbol{\nu_e + \overline{\nu}_\mu}$) - scattering end point energy 148 keV

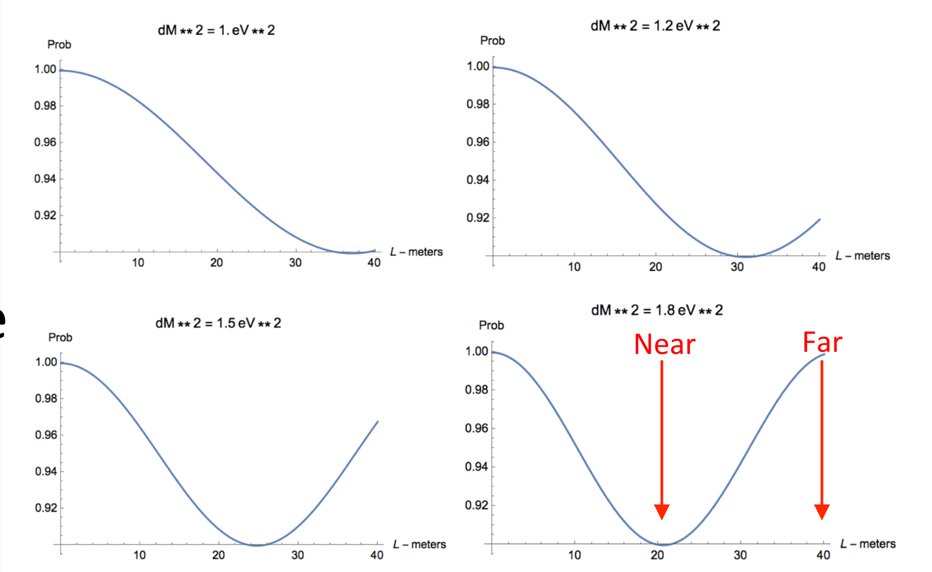




Signal/Background Strategy

- **Looking for up to ~10% disappearance over 15-40 m distance**
  - ~1,000 CEvNS events 3 years.
  - Near/far cancellation to reduce systematic errors.
  - Can move detector to multiple positions (sample L/E).

New Reactor-4 result of 7eV^2 -> ~5m oscillations

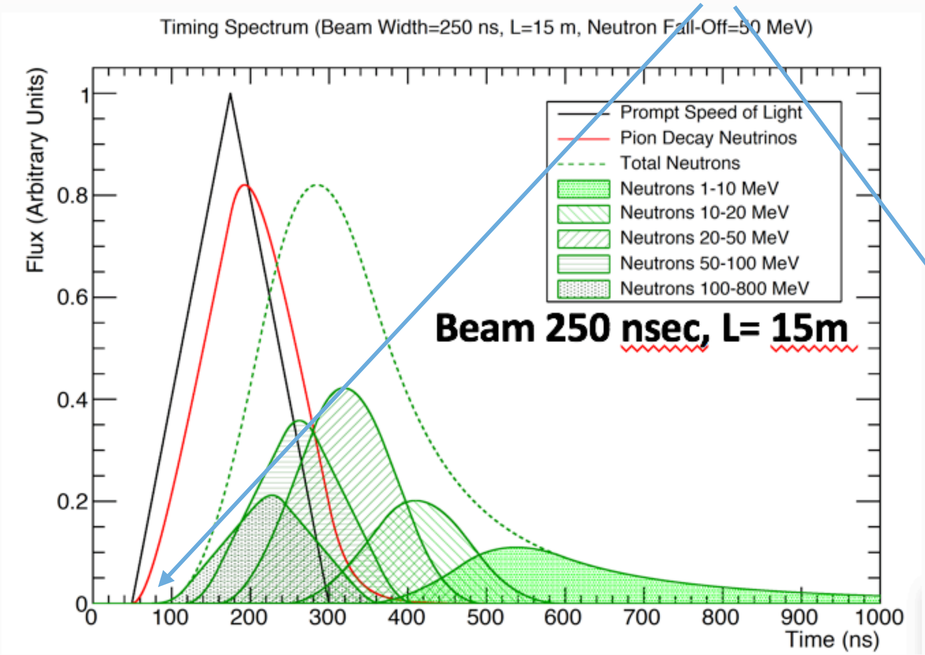


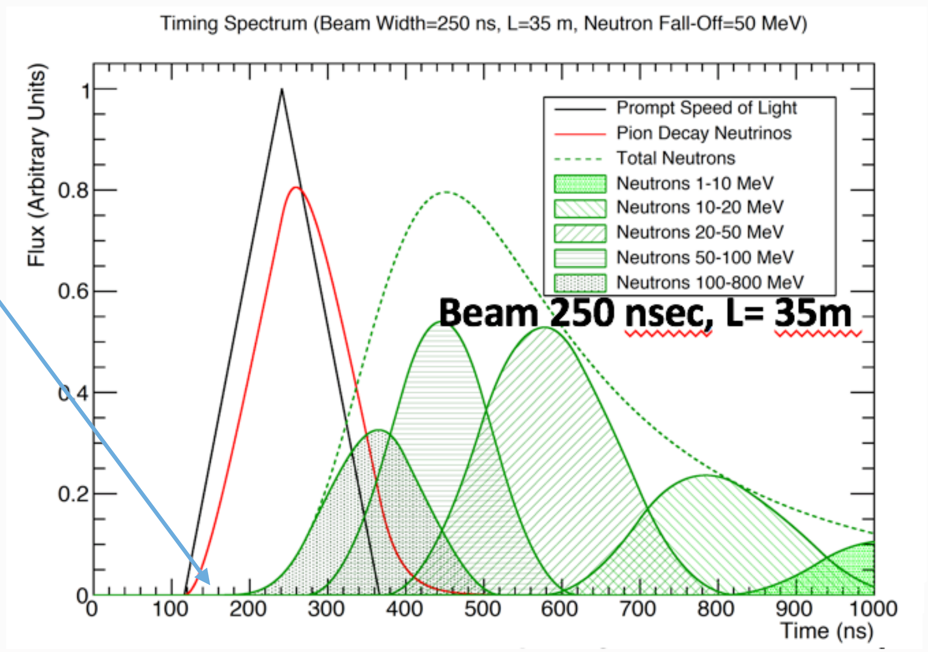
- **Background mitigation crucial, attack with flexible strategy**
  - Fast (~nsec) detector and beam 2.9x10^{-6} duty factor (250 nsec)
  - Variable beam width reduced to 30 to 100 nsec for systematic checks.
  - Instrumented and integrated veto.
  - Beam off subtraction (precise, but affect statistics on signal)
  - Particle ID – separate electron and nucleon events > 10^2
  - Shielding – can adapt as neutron background measured.

Beam Neutron Backgrounds

- Neutrons from the target, and interactions in the surrounding material.
- No beam off subtraction and veto provides minimal rejection.
- **Prompt Signal**: EJ-301 detectors measured bulk neutrons < 70 MeV. Expect ~100 nsec (200 nsec) neutron free window near (far) position.
- **Delayed Signal:** Low (slow) energy neutrons efficiently rejected with concrete/water shielding.

Neutrino window free of Neutrons: More upstream steel shielding increases window

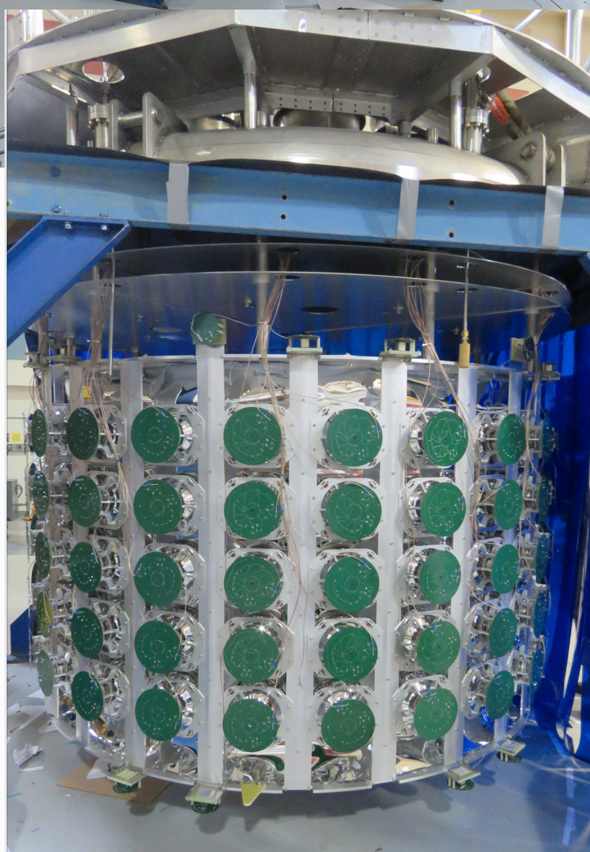




Plot from R. Cooper (NMSU, LANL)

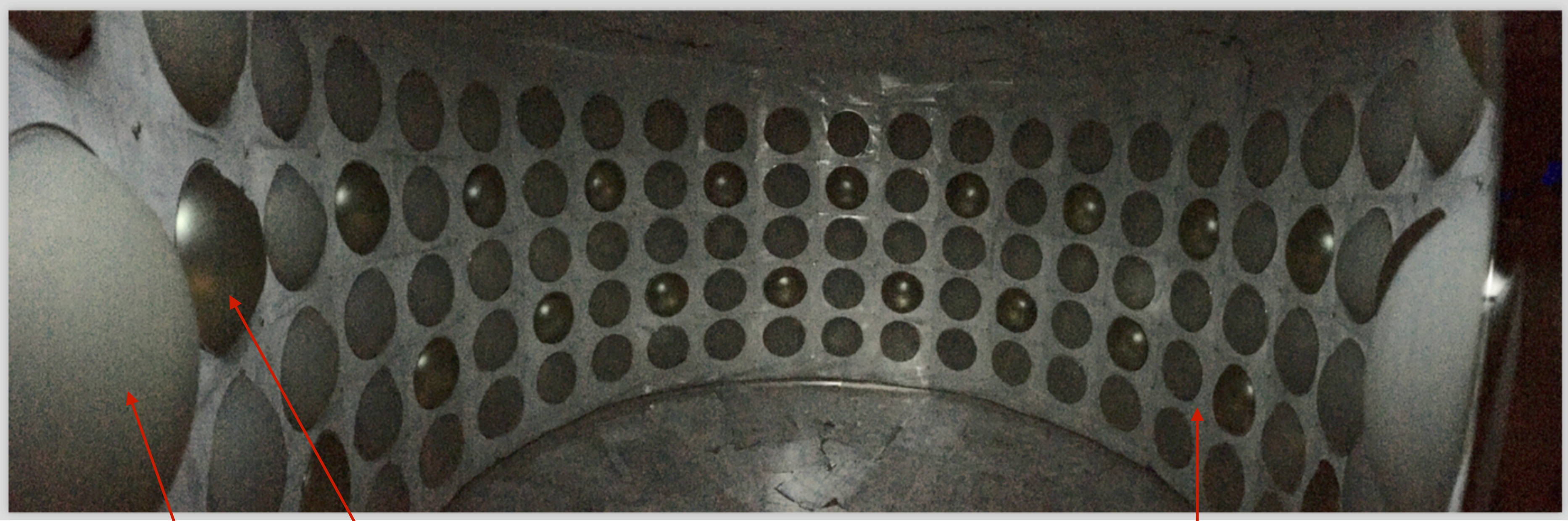
Building CCM in ~4 months was a Herculean Team Effort!

Students
Alex Diaz (MIT)
Jose Palata (UNAM)
Nick Kamp (UMich)



Complete PDS System Test at LANL with Coherent Captain-Mills (CCM) Detector

- LAr cold test entire SBND PDS system: 96 TPB coated + 24 uncoated PMT's, mounts, cables, feedthrus, HV, electronics, trigger, DAQ, calibration, simulations and data analysis.
- Built detector August-Dec 2018 at LANSCE/Lujan center (100 kW neutron/stopped pion neutrino source)



TPB coated PMTs

Uncoated PMTs

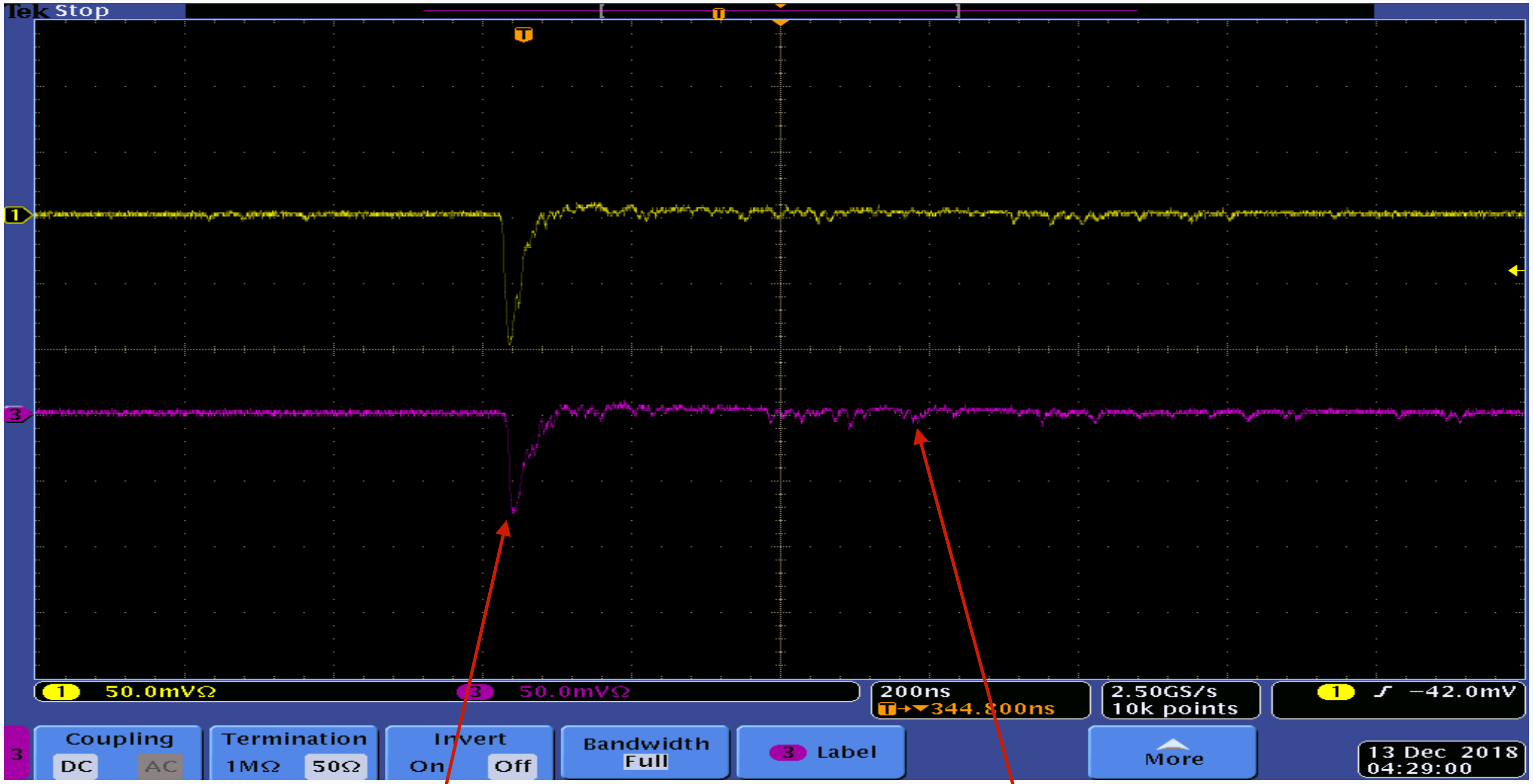
TPB coated reflector foils. Maximize light output to detect coherent neutrino-nucleus scatting

- Built detector August-Dec 2018 at Lujan center (100 kW neutron/stopped pion neutrino source)
- **10 tons of LAr filled Dec 10**
- System stable, low noise, long DAQ runs.
- One bad HV channel found (breakdown).
- 20TB of data taken over ~8 beam days

First Results from System Testing: Scope Traces

- Single PhotoElectron ~5 mV
- RMS noise < 0.1 mV

Cosmic Ray



Singlet light ~6nsec

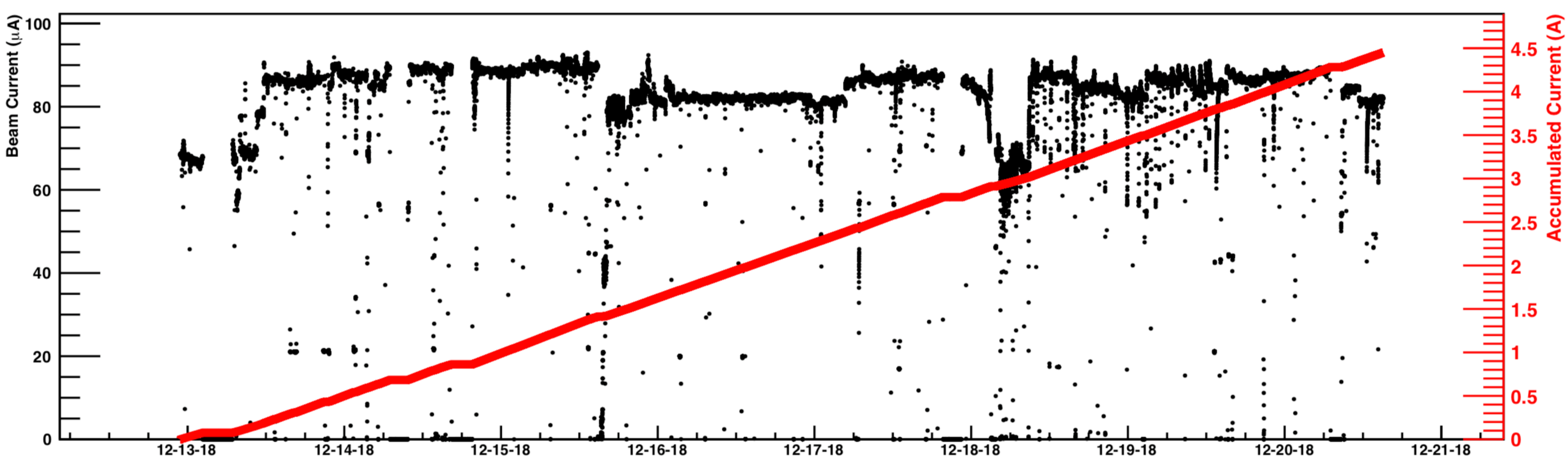
Triplet light ~1.6 usec

- Electrons have low singlet/triplet ratio
- Nucleons have high singlet/triplet ratio

Pulse shape discrimination
Particle ID

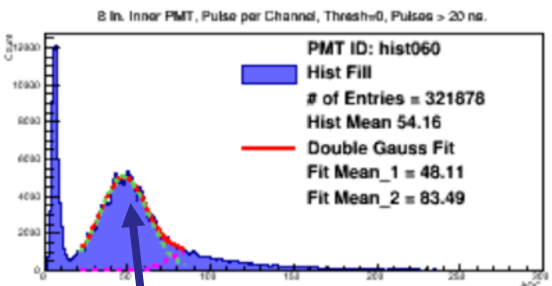
CCM Lujan Run: Dec 12 to 20th

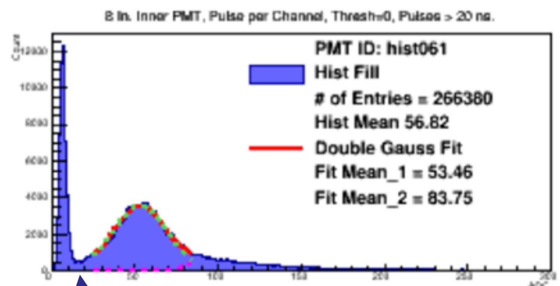
- Beam stable with high uptime and ~82 uA current, total 1.5E20 POT
  - 3871036 beam triggers with no steel shielding
  - 2482616 beam triggers with steel shielding
- Detector ran stable,
- LAr loss rate of ~1.5” day, require 3 top offs during run.
- DAQ performed well, 20 Tbytes of data taken.

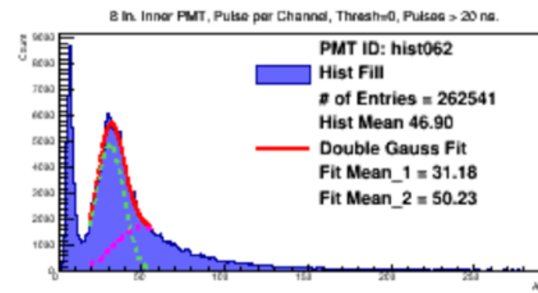


Searching for Single PEs in Pre-Beam Data (T. J. Schaub)

- One dead PMT's. Two with bad SPE gains.
- Can see clear single PE peak and noise wall





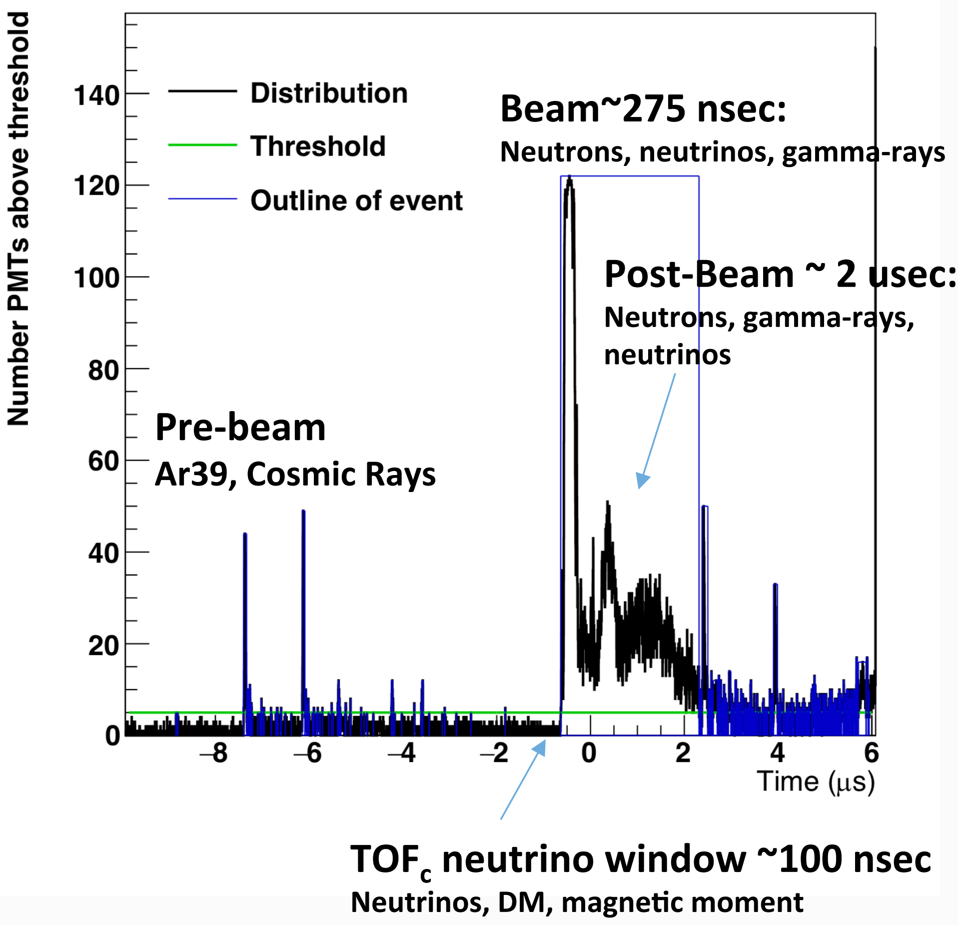


Clear Single PE peak

Threshold ~0.3 PEs

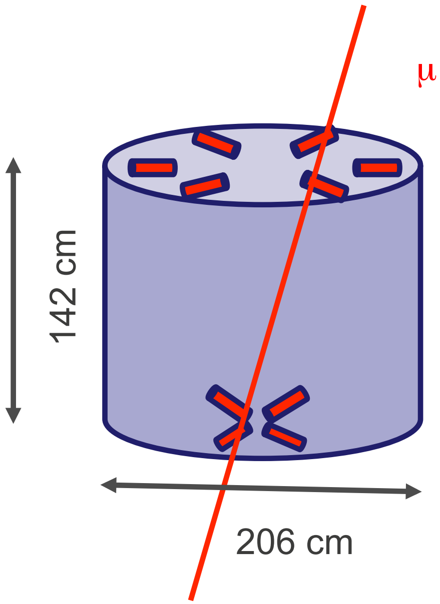
Beam Event Definition, Global Event View

- DAQ readout window 16 usec: 10 usec pre-beam, 4 usec post beam.
- Find all PMTs for a given time sample that pass a threshold (~0.3 PEs)
- An event is consecutive samples with 5 or more PMTs above threshold
- Amplitude and Integral are calculated as the sum amplitudes and integrals of the individual PMTs for the event range



Sanity check: cosmic-ray muons (Dan Paulson)

- Cosmic ray muons reach the Earth surface at a rate ~ 1/cm^2/minute
- Their flux is proportional to cos2(θ), θ being the zenith angle



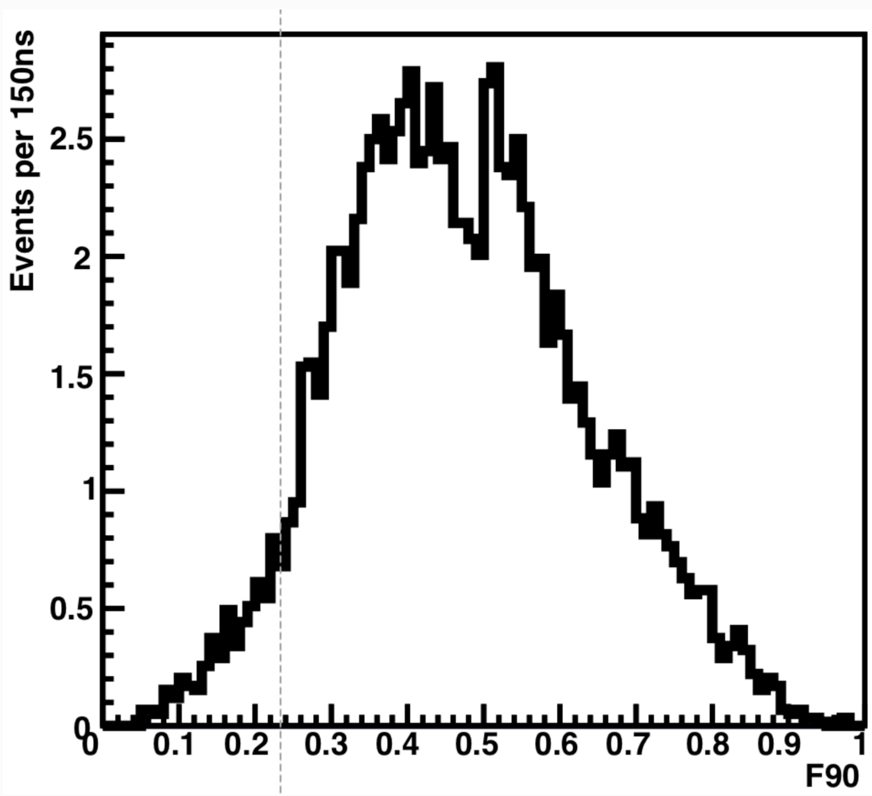
- Most of them are Minimum Ionizing Particles and deposit ~ 2.1 MeV/cm in LAr
- Muons going through the top and bottom of the tank deposit > 300 MeV
  - They produce more than 12E6 photons in the tank, HUGE signal!
- Based on the shape and size of the inner tank their expected rate is 331 muon/s
- Muons just crossing the top of the tank are expected with a rate of 555 muons/s

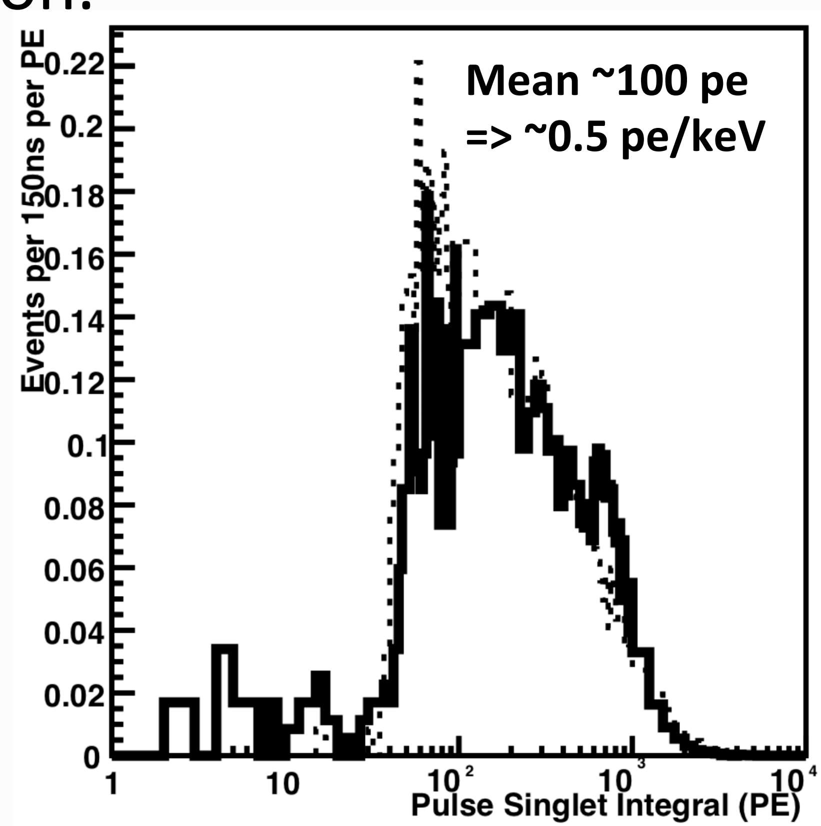
With Simple Cuts

- 334 events compatible with muons found in 1.0 s, **equivalent to muons/s**
- Since we are not requiring PMTs from the top region to fire we **expect a rate between 331 and 555 muons/s**
- **The measured rate is consistent with the expected rate** and possibly some shielding resulting from the east side of the building being below grade.

Ar39 Rates and Energy Calibration

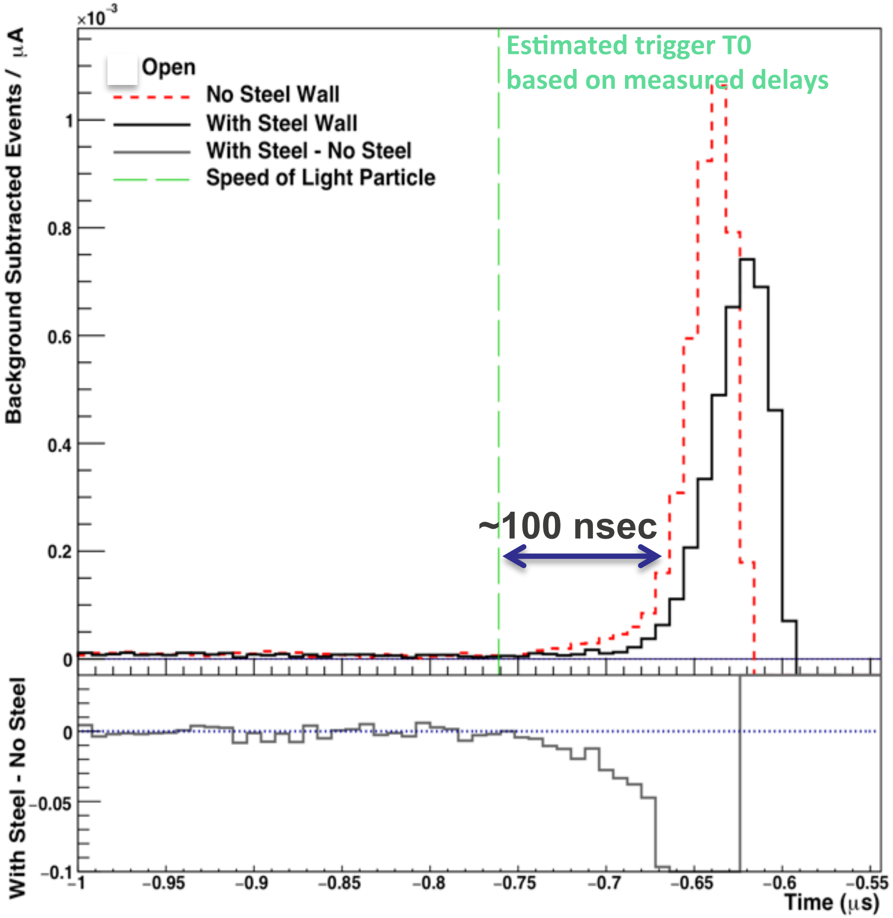
- Beta decay endpoint 565 keV, mid energy 219 keV.
- Scan for events in pre-beam region
- Measured rate ~1.4×10^{-4} per 150 nsec window, consistent with expectation.





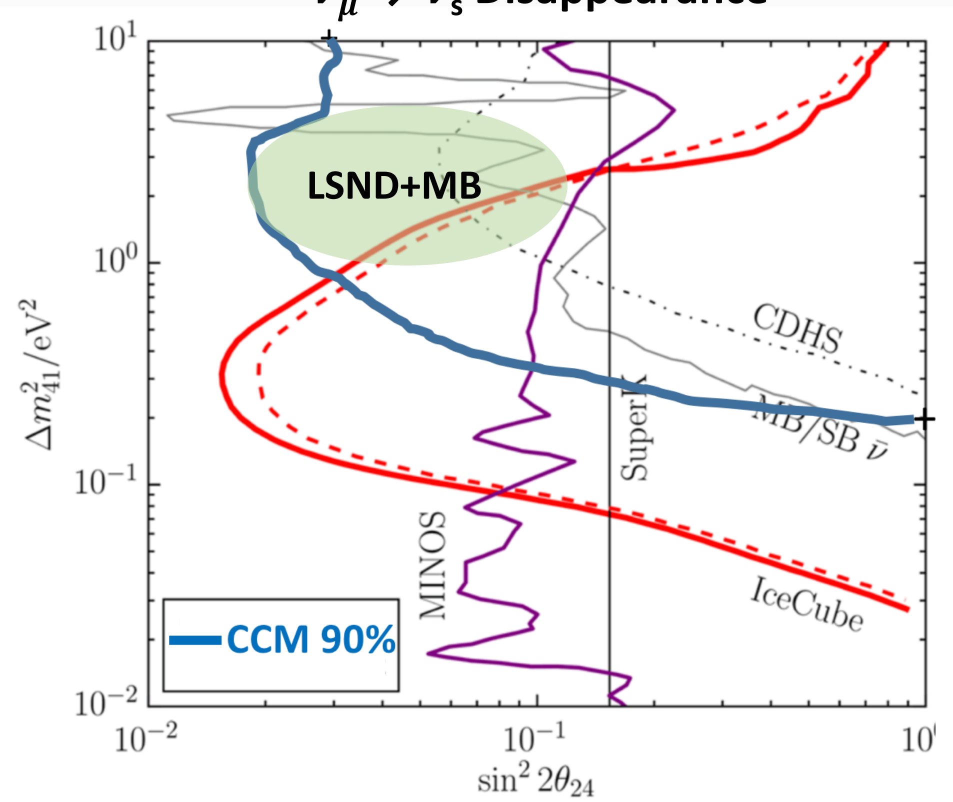
Beam Events with and without Shielding

- Observe beam neutron turn on relative to speed of light particle (~100 nsec)
- More shielding decreases neutron rate and increases timing shift
- Gives confidence more steel shielding will increase neutron free region



CCM Measuring Muon-Neutrino Disappearance with Neutral Current Coherent Neutrino Scattering

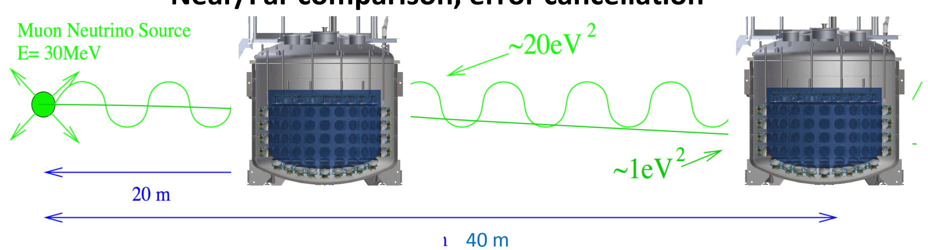
$\nu_\mu \rightarrow \nu_s$ Disappearance



- **Prompt 30 MeV monoenergetic muon neutrinos:**
  - L/E with no energy smearing.
  - Source position error 8 cm (~0.4%).
- **Delayed neutrinos**
  - High rate signal, high energy (148 keV), different backgrounds.
- **Neutral Current Coherent Ar Scattering:**
  - Flavor independent, all active neutrinos detected, deficit implies oscillation into sterile neutrinos.

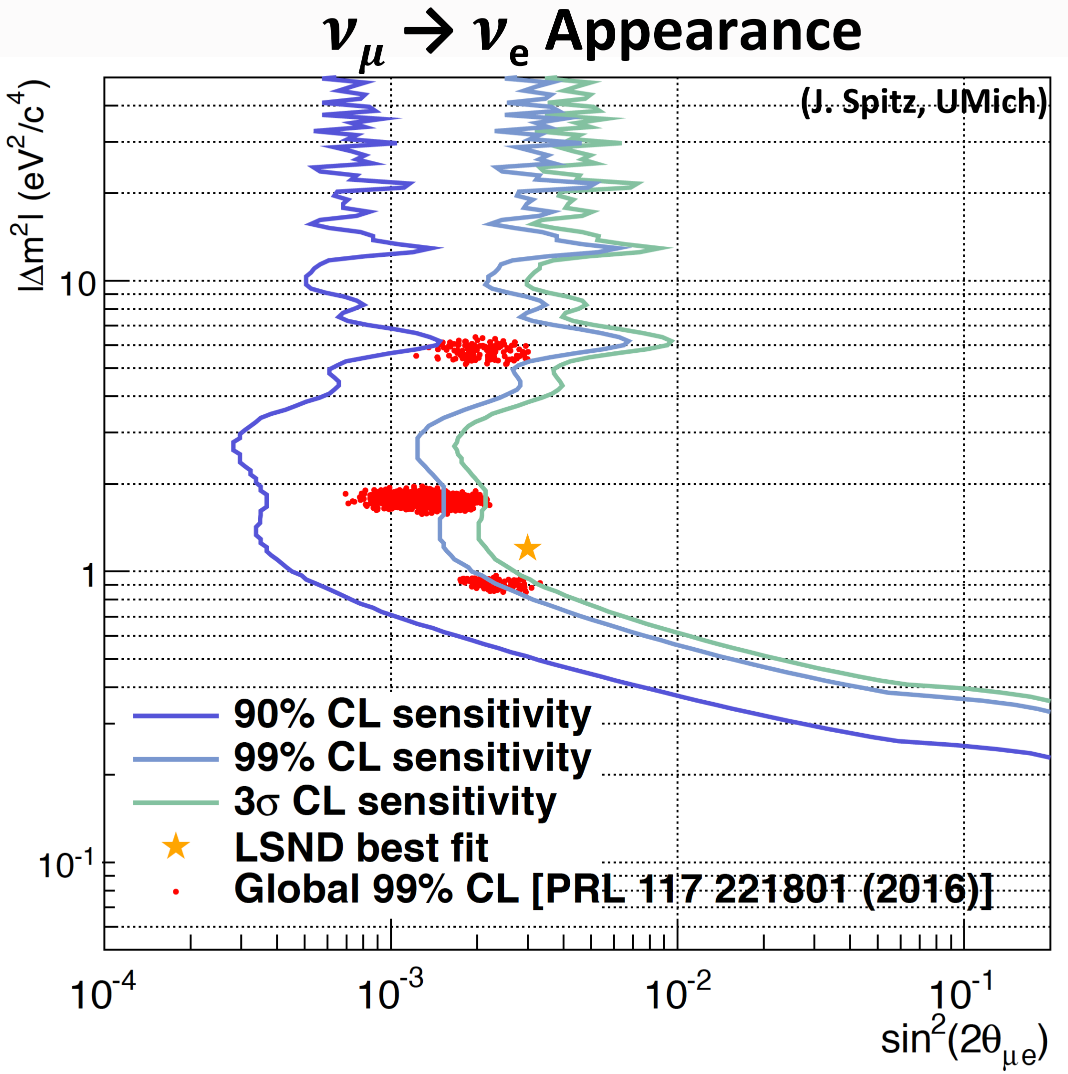
Neutral Current Disappearance Pattern in a Two Detector Setup

Near/Far comparison, error cancellation



- **CEvNS muon disappearance signal would provide smoking gun proof of sterile neutrinos at the LSND+MiniBooNE mass scale.**

CCM Sensitivity to "3+1" sterile neutrino hypothesis (3-year run)



- Can prove/disprove at ~3σ LSND 3+1 sterile neutrino hypothesis.
- Five year run would approach 5σ!
- If no signal, can rule out world best fit at better than 90%

Summary

- Build CCM detector in 4 months and ran for a week at the end of 2018.
- Demonstrated stabile operations, 0.5 PE/keV response with a PMT based LAr detector.
- Will use TOF to isolate mono-energetic neutrinos from neutron backgrounds.
- Calibration and beam running from May-Dec 2019 will establish CEvNS signal.
- Will add more shielding and push for shorter beam width of 100 nsec to improve signal separation.
- Building upgraded detector CCM200 with twice the photocathode coverage and begin muon neutrino disappearance run in 2020.
- Seeking funding for a second CCM detector to improve sterile neutrino and DM search (NSF, DOE Dark Matter FOA, etc)

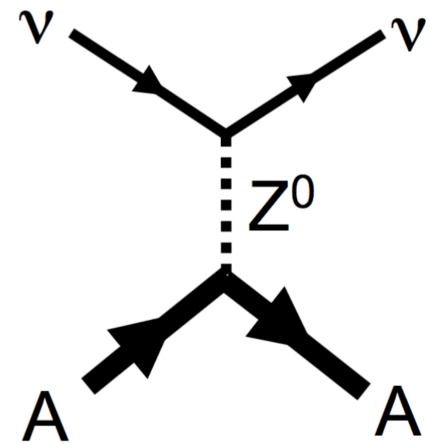
Backups: The Neutrino Scatters Here!

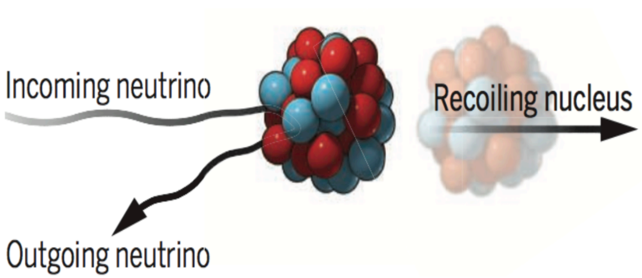
Slide from Kate Scholberg

Coherent elastic neutrino-nucleus scattering (CEvNS)

$$\nu + A \rightarrow \nu + A$$

A neutrino smacks a nucleus via exchange of a Z, and the nucleus recoils as a whole; **coherent** up to $E_\nu \sim 50$ MeV





- **Low energy nucleus recoil E ~ 10's keV**
- Well-calculable cross-section in SM: SM test, probe of neutrino NSI
- Dark matter direct detection background
- Possible applications (reactor monitoring)

$$\frac{d\sigma}{d\Omega} = \frac{G^2}{4\pi^2} k^2 (1+\cos\theta) \frac{(N-(1-4\sin^2\theta_W)Z)^2}{4} F^2(Q^2)$$

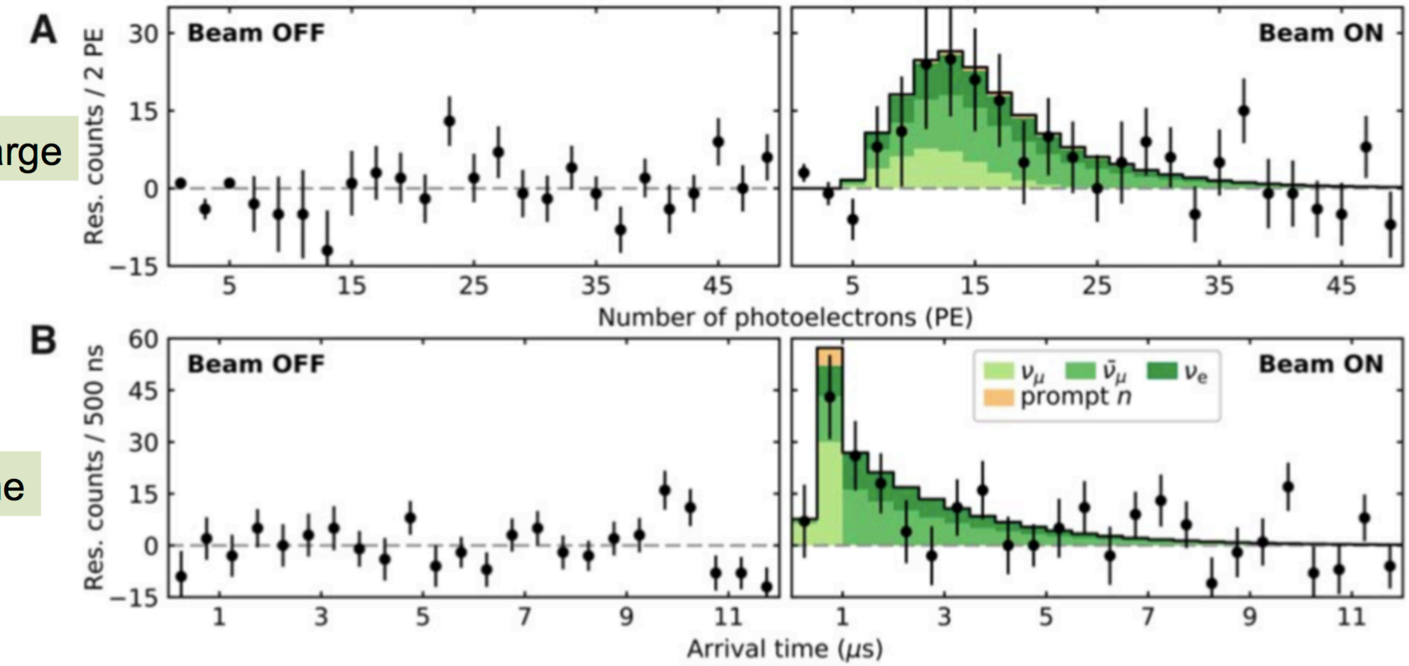
$$\boxed{\propto N^2}$$

Coherent Neutrinos have been Recently Observed at SNS

First light at the SNS with 14.6-kg CsI[Na] detector

Charge

Time



Observation of coherent elastic neutrino-nucleus scattering

D. Akimov[1,2], J. B. Albert[3], P. An[4], C. Awe[4,5], P. S. Barbeau[4,5], B. Becker[6], V. Belov[1,2], A. Brown[4,7], A. Bolozdy...

+ See all authors and affiliations

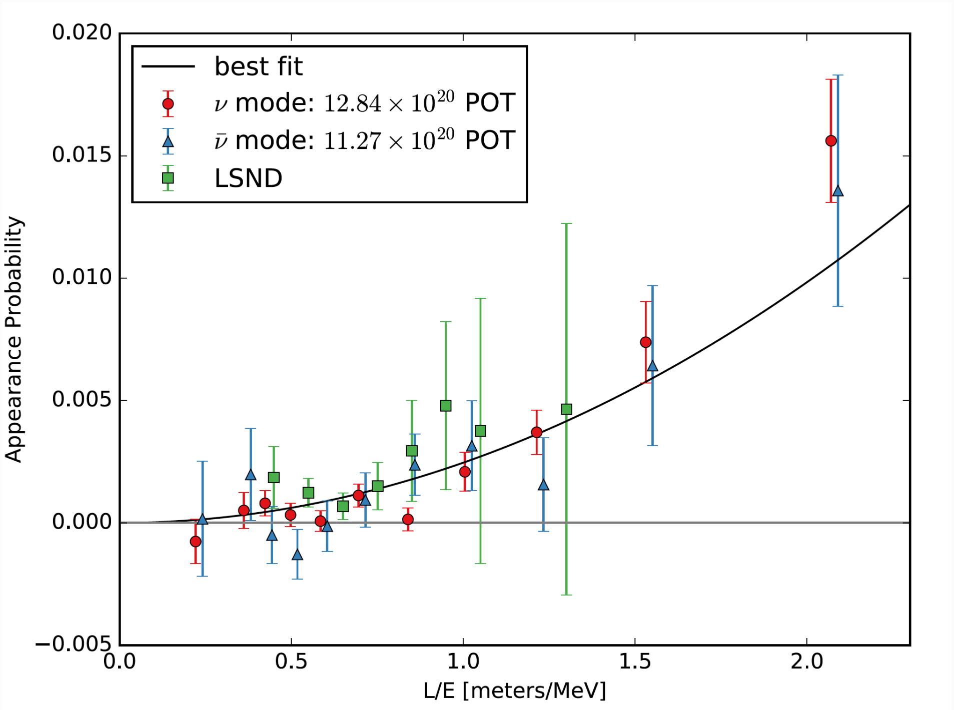
Science 03 Aug 2017:
eaao0990
DOI: 10.1126/science.aao0990

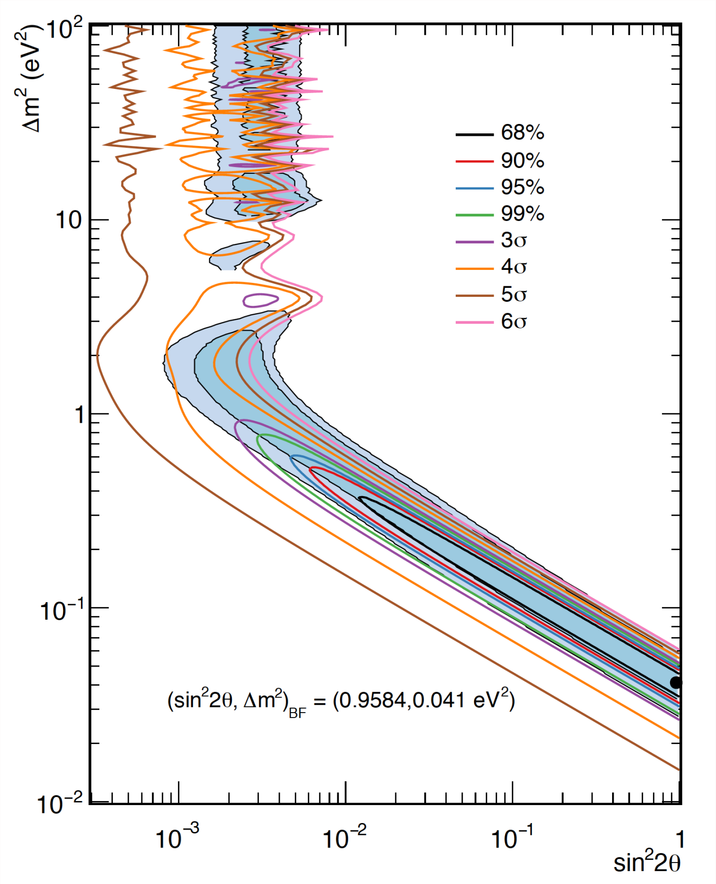
Peer Reviewed
← see details

D. Akimov et al., *Science*, 2017
http://science.sciencemag.org/content/early/2017/08/02/science.aao0990

Slide from Kate Scholberg

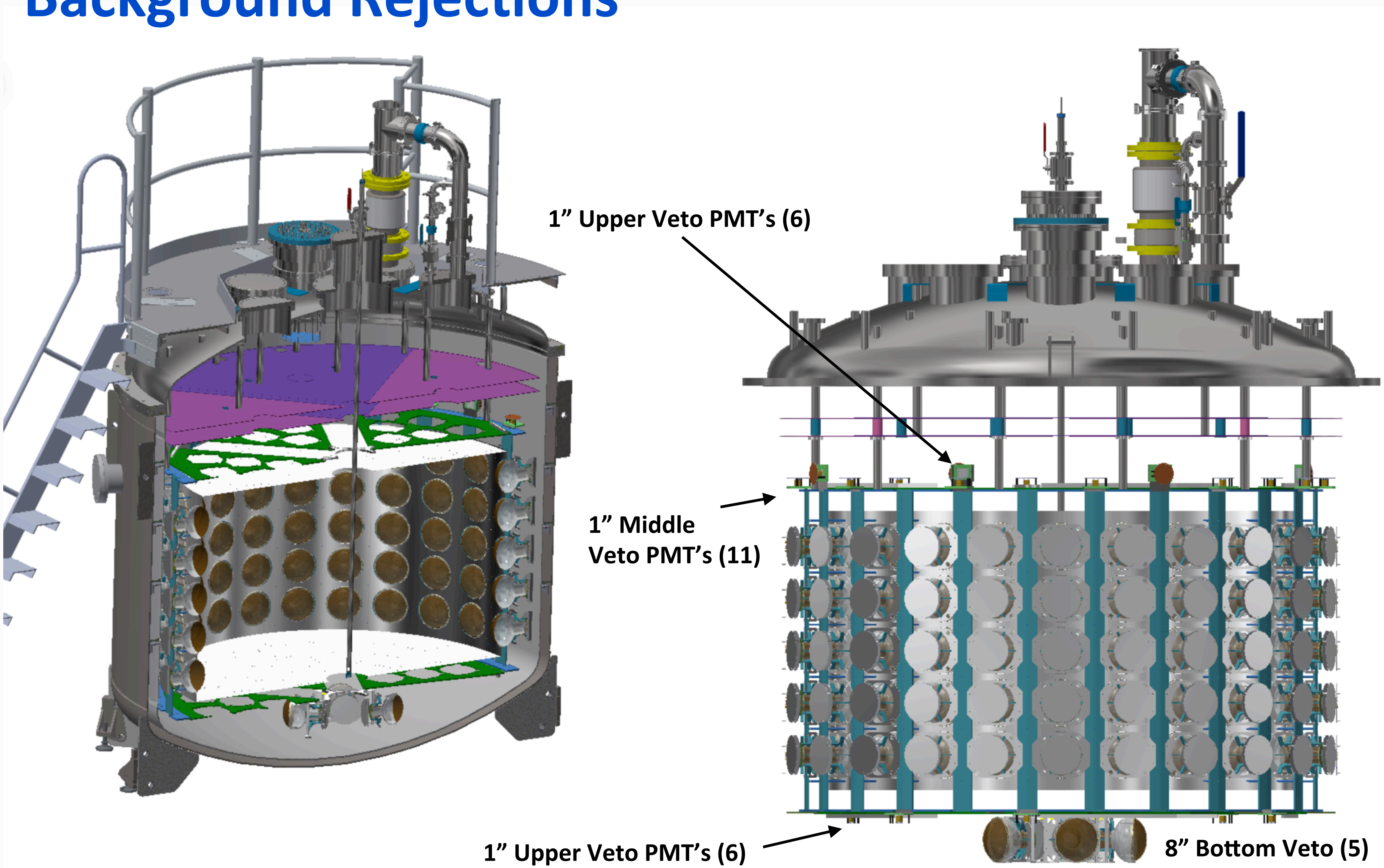
MiniBooNE New Oscillation Results





- **MiniBooNE is consistent with LSND excess, and combined is 6σ**

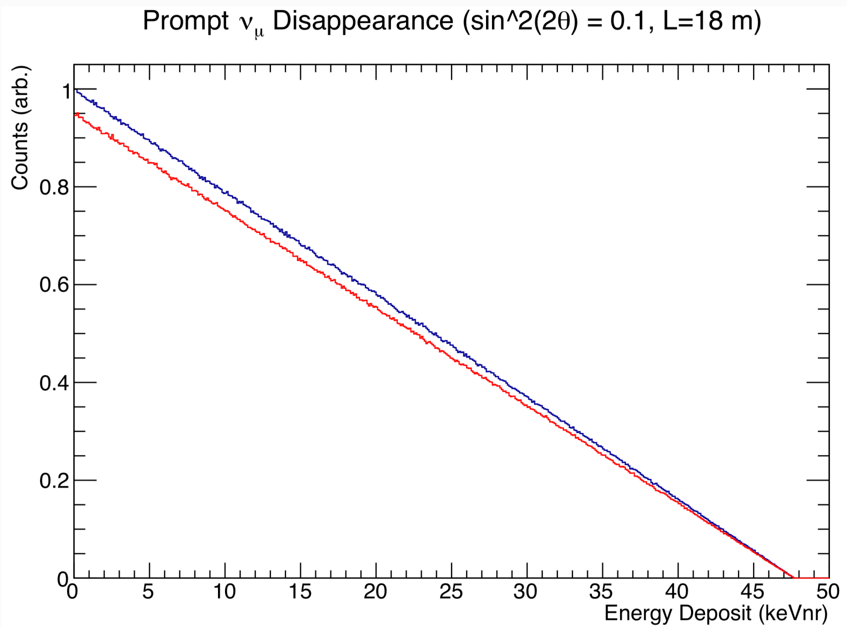
Integrated and Active Veto Regions for Background Rejections



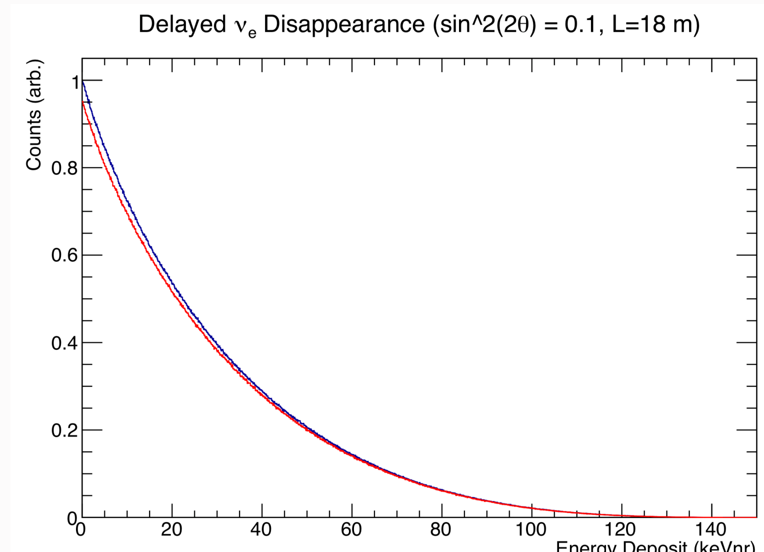
- 7 tons LAr Fiducial volume, 3 tons LAr Veto (2-3 radiation lengths).
- Active Veto region crucial to rejecting cosmic rays and other external backgrounds.
  - 1 MeV gamma: 2 rad lengths: 100 keV x-ray: 10 rad lengths: 1 MeV neutron: 1 scatter length

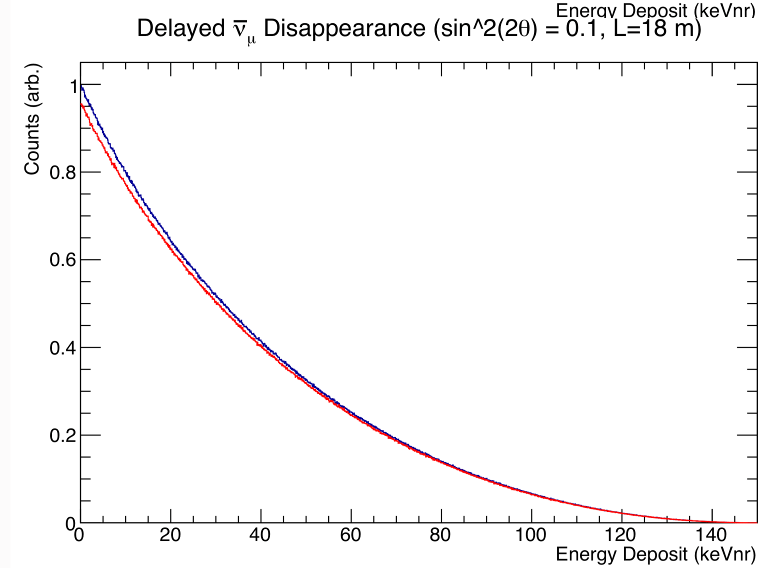
Coherent Neutrino-Nucleus Scattering Energy Spectrum

Prompt Neutrinos E_{muon} **= 30 MeV**



Delayed Neutrinos





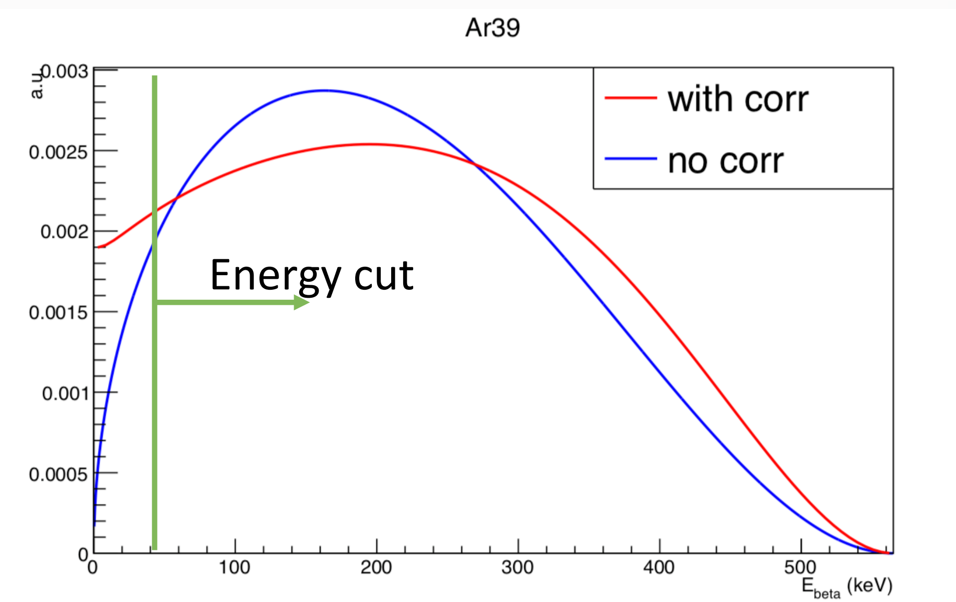
Random Backgrounds for CEvNS

- **Cosmogenic**: about ~200 Hz. Beam duty factor + overburden + veto, will reduce to 10 (130) events/year.
- **U/Th**: Dust and PMT glass contains U/Th ~MeV beta/gamma. Expect ~10 Hz per PMT. Analysis tricks such as fiducial cuts, or large charge in a single PMT cuts will reduce significantly. Will need to pay attention to cleanliness during detector construction. Expected background small.
- **Beam off subtraction will measure these backgrounds extremely well.**

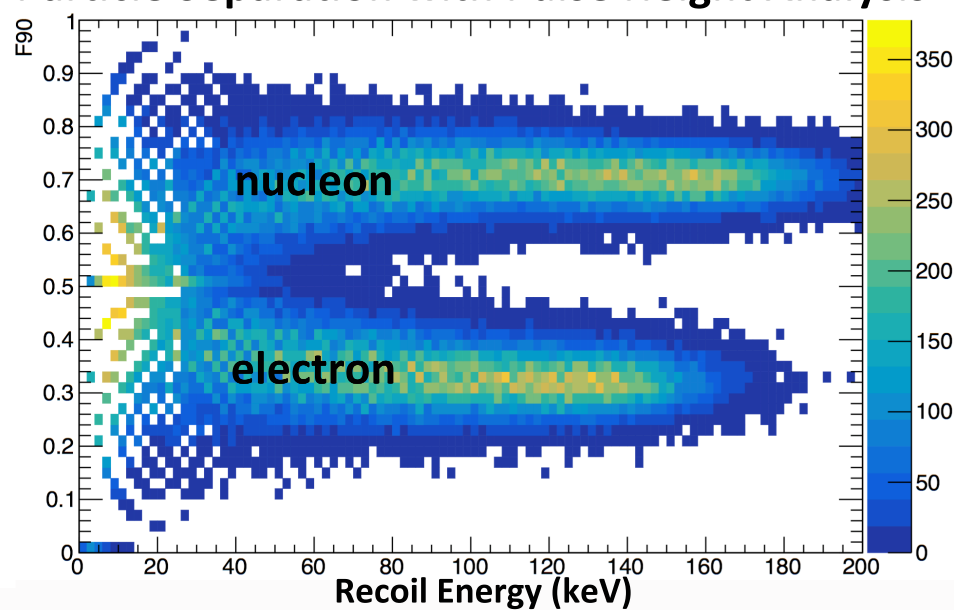
- **295 nsec beam good, but some running with shorter beam time of 30 or 100 nsec would provide systematic check on background estimates.**

Random Backgrounds for CEvNS

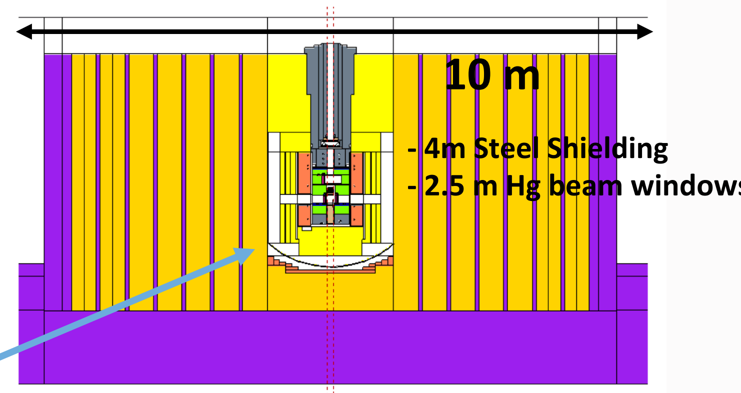
- ^{39}**Ar**: 565 keV endpoint $\boldsymbol{\beta}$ emitter: In CCM detector, estimate 7.5 kHz rate.
  - Beam rejection factor ~10^5
  - energy cut (~10^1), pulse height discrimination (10^1 to 10^5)
  - Measured precisely by beam off running.
  - Subtraction increases signal statistical error from 2.7% to 3.5% (prompt), minimal effect on delayed signal.



Particle Separation with Pulse Height Analysis



Detailed Target MCNP Simulations (Charles Kelsey P-27)



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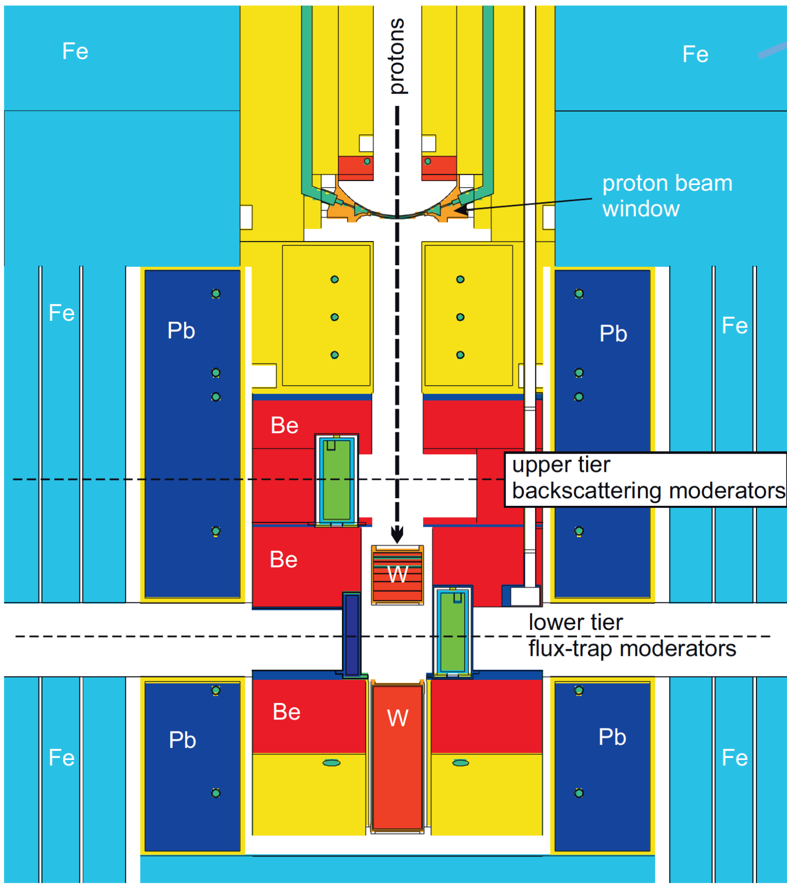
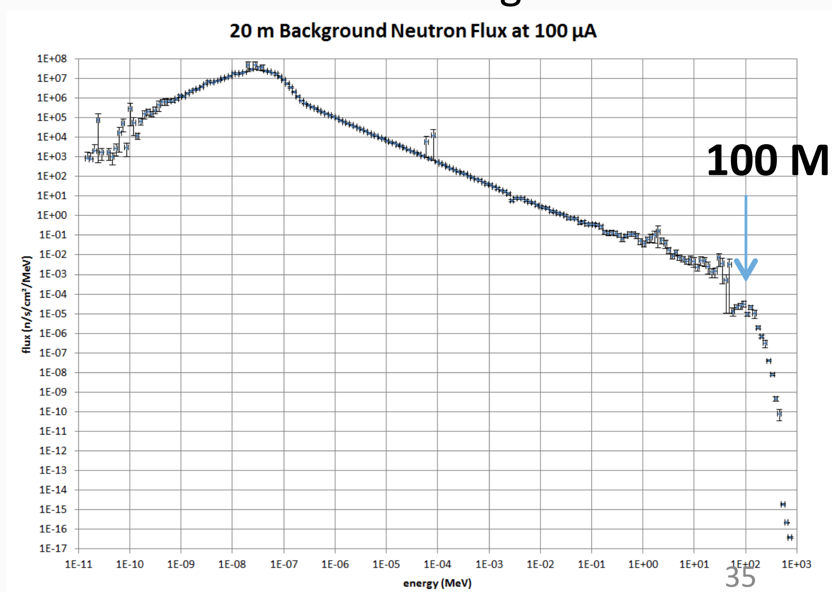
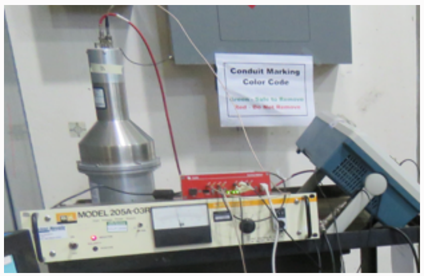


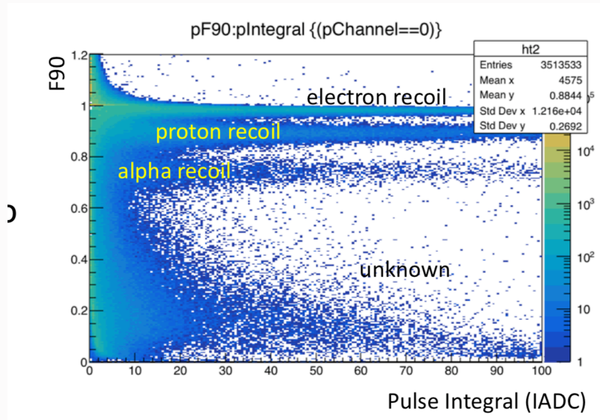
Fig. 1. Elevation view of the Lujan Center's TMRS geometry used in our calculations. The main components are labeled: split tungsten target (W), beryllium reflector (Be), lead reflector–shield (Pb), and the steel reflector–shield (Fe).

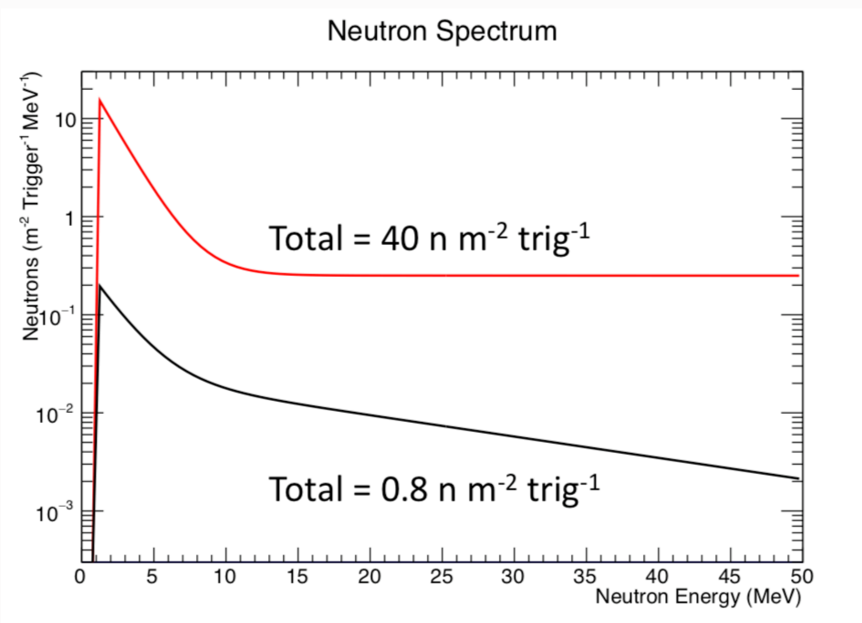
- Simulations has confirmed hand calculated flux of ~4.74×10^5 nu/cm^2/s at 20 m
- Horizontal extend of neutrino production at the source of 8 cm (1 sigma position error)
- Simulated neutron backgrounds



Initial Neutron Rates and Spectrum (TOF) Measurements with EJ-301 Neutron Detectors

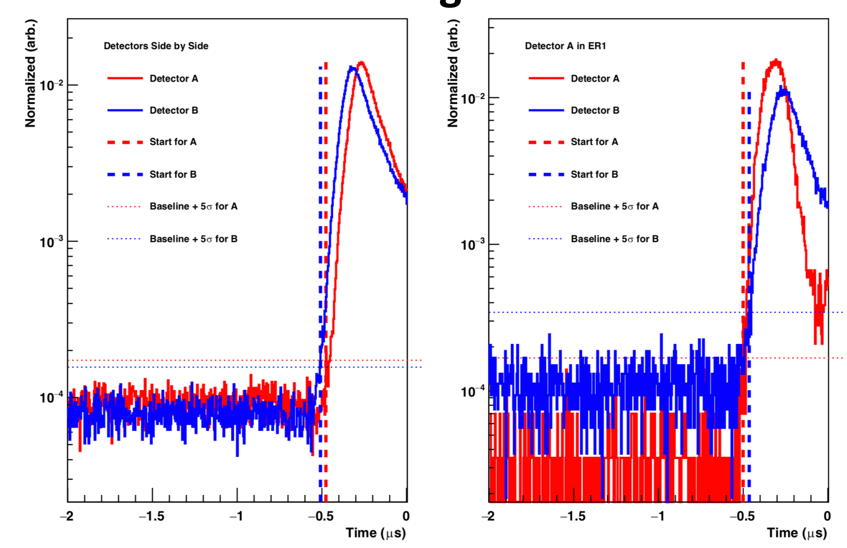






Neutron Reduction with 26" Steel

Neutron time of flight over 10.8 m



Leading edge of neutrons ~76 MeV which is 168 nsec delay over 20m

Timing Delays Measured (Scope): Working out a few missing pieces – dealing with legacy knowledge/equipment

Future upgrades to improved timing delay stability and simplicity, i.e. faster coils, direct cable from coil to detector digitizers, etc

<u>20 m n-TOF table</u>

c	67 ns
800 MeV	79 ns
500 MeV	88 ns
200 MeV	118 ns
100 MeV	156 ns
50 MeV	213 ns
20 MeV	328 ns